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A design of *in-situ* detector of charged lunar dust (DCLD)

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ABSTRACT

Charged dust widely exists on the surface of the moon, which is considered to be closely related with many natural phenomena. China's Chang'E-5 lunar mission plans to monitor the charged characteristics of electrostatically levitated dust on the lunar surface in an economical and effective way. The designed detector consists of two probes, the reference probe and the measuring probe. Each single probe consists of two grids and a sticky quartz crystal microbalance. The sensitivity coefficient of measuring probe is S_M=(8.002±0.510)×10^{-9}g/Hz·cm^2, and that of reference probe is S_R=(9.137±0.369)×10^{-9} g/Hz·cm^2 under the test. By comparing the measurement results of two sets of probes, the mass proportion of dust with different charge/mass ratio of suspended lunar dust can be obtained. These results measured on the lunar surface would be helpful for analyzing the levitation mechanisms and motion characteristics of lunar dust.

1. Introduction

Dust is the main components of the cosmos, which contains abundant information about the evolution of the universe [1]. In solar system, dust widely exists in interstellar space and surface of planets. These dust particles are often charged, due to solar UV radiation, plasma, and other factors. Among them, the charged dust on the moon surface attracts the most attention of researchers. On the one hand, it may be closely related to many natural phenomena, and it is widely known as Ḧorizon glow⁼ it is believed that the charged dust particles scattered the sunlight when it ejected by the electrostatic field on lunar surface; on the other hand, the charged dust particles will have stronger adhesion force, which may pose a more serious threat to lunar probes [2].

Since the Project Apollo, human beings have been exploring lunar dust diligently. For example, the LEAM probe carried by Apollo 17 mission used thin plastic films and grids to jointly detect the mass and velocity of lunar particles which entered the probe [3]. In 2013, another NASA's spacecraft, lunar atmosphere and dust environment Explorer (LADEE), launched Lunar Dust experiment (LDEX) [4], which used collision ionization method to detect dust particles in the outer atmosphere of the Moon. In the same year, China's Chang' E-3 (CE-3) used a solar cell probe (SCP) and a Sticky Quartz Crystal Microbalance (SQCM) to detect dust accumulation in landing site caused by both anthropogenic and natural factors [5–7].

These explorations bring insight into a further understanding for human beings to solve the mystery of lunar dust [8]. Researchers established several types of models to describe the transport characteristics of lunar dust [9–13]. However, as many studies have pointed out, there are still many controversies about the lunar dust even such exploration that had been carried out in history [14]. Currently, many organizations have carried out their lunar dust exploration program, such as Luna glob PML detection experiment of Russia [15], SELMA of ESA [16].

This paper mainly describes the design and working principle of the detector of charged lunar dust(DCLD), which will be carried on China's Chang'E-5(CE-5) mission. CE-5 was scheduled to launch at the end of 2020. Its main task is to collect lunar samples and return to Earth. The DCLD equipment is one of the engineering parameters measurement payloads, and it will be installed on the top of CE-5

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lander at a height of 2.0 m. It will start working after the completion of the CE-5 sampling and returning mission, and will work for a certain period for measuring the charged characteristics of lunar dust in the natural environment of the moon.

2. General design

2.1. System generalization

As we know, under the action of Coulomb force and gravity, the lunar dust particles are leaping up from and falling back to the Moon's surface. In this process, the charge-mass ratio of the dust particles plays a critical role, and it contains lot information about the lunar surface electrostatic field and plasma environment. It is also an important parameter for developing lunar dust removal technology, such as the electro-dynamic screen (EDS) technology. Therefore, it is necessary to measure the natural charge-mass ratio of lunar dust.

The DCLD is mainly used to detect the charged characteristics and to obtain the distribution of charge-mass ratio of naturally suspended lunar dust in the daytime. Due to engineering limitations, the Chang'E-5 DCLD needs to achieve high sensitivity measurement of charged lunar dust, and it must be light weight ($\leq$0.5 kg) and low power consumption($\leq$5W).

For the charged characteristics of slow-moving dust particles detecting, the most common method is to use a Faraday Cup, which has been used in scientific research for 40 years at least, such as in the sand research, the smog investigation and also in the space science field [17–22]. To measure the charge mass ratio of dust using a Faraday Cup always need an Electrometer and a high accuracy Electronic Balance. Therefore, it is difficult to develop for space application. Another instrument named Electrostatic Lunar Dust Analyzer (ELDA) based on the combination of a Dust Trajectory Sensor (DTS) with an electrostatic deflection could provide the charge, velocity and mass of particles [23]. However, the system of ELDA is quite complicated, and its size is a little large for Chang'E-5 mission.

In Chang'E-3 mission, SQCM had been used to measure the accumulation of lunar dust [6]. SQCM is a resonant micro-sensor with high sensitivity, low weight and low power consumption measurement. It has been used to measure Martian dust in Mars exploration [24] and been considered to be used to measure comet Rosetta dust [25]. In Chang'E-5 mission, we still use SQCM as a means to measure the accumulated mass of tiny dust particles. The difference is that, we install two grids, like a Retarding Potential Analyzer (RPA) above the SQCM as a sensor to obtain the charged information of dust particles, and we use two sets of structure (RPA + SQCM) to measure the charge-mass ratio of lunar dust (Schematic design of the DCLD been shown in Fig. 1).

As shown in the schematic, there are two sets of RPA + SQCM in DCLD. The measuring probe is on the left, and the reference probe is on the other side in Fig.1. The structures of the two sets of probe are the same as each other, but a voltage will be applied in the measuring probe grids (RPA-M). The electrostatic field will prevent the dust with specific charge to pass through the grids. To compare the two probes measure results, and combine the swept voltage, we can get the distribution of the lunar dust with specific charge ratio.

2.2. RPA

The RPA is one of traditional plasma diagnostic tools, and it can be used to measure the density, temperature, composition and moving speed of ions. It has been used for 60 years as in-situ measurement equipment for the energy of space plasma. Generally, a RPA consists of three or four electrostatically-biased mesh grids, and a conductor placed behind the grids to be used as a detector [26]. Only two mesh grids are needed in our design, which are the entrance grid and the sweep grid respectively, as shown in Fig. 2.

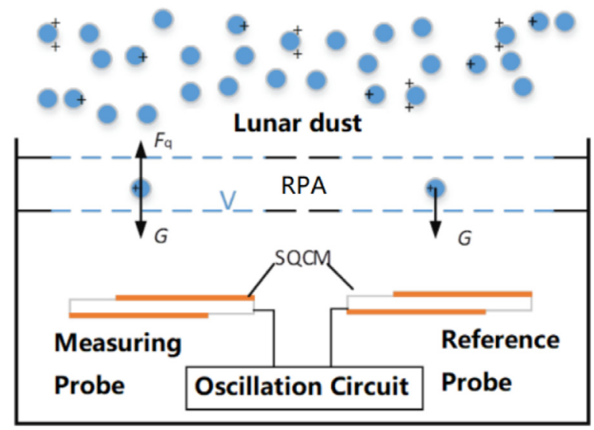

Fig. 1. Schematic design of the DCLD.

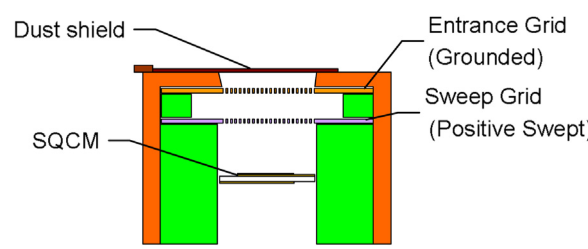

Fig. 2. Diagram of one probe.

The main function of RPA is to provide a uniform electric field, and act on charged lunar dust particles. The first grid is connected with the Chang'E-5 ground to eliminate the influence of the floating potential of the lunar module; the second grid is connected with a swept voltage, which could scan at zero volts, and increase with preset steps to a high voltage. The distance between two grids is 12 mm in design, and also the diameter of mesh area is 12 mm. Other information about the mesh size and structure is shown in Fig. 3. Such mesh layouts has enough transmittance and obtain a uniform parallel electric field. According to the calculation, the geometric transmittance of the grid is 85.4 % as a uniform electric field is generated in the central area of the grid. For example, when the sweep voltage is +1.5 V, the electric field potential and intensity are shown in Fig. 4. If we change the sweep voltage, we can find that the results are similar for other sweep voltages.

2.3. SQCM

Quartz Crystal Microbalance (QCM) is usually used to monitor the outgassing and degradation of molecular contamination in most space applications [27], however, it is also used to measure the mass of particles with a sticky film [28], as mentioned above.

In order to improve the adhesion between solid particles and QCM electrode, a sticky film is coated on the surface of crystal. Researchers in China had conducted a one-year survey with SQCM for lunar dust detection at Chang'E-3 mission.

Chang'E-3 SQCM measuring instrument is located in the temperature control module of the lander. The working temperature of SQCM is about (- 10 ~ 60 °C) on the lunar surface, and it changes slowly. This indicates that SQCM can be used to measure the accumulated mass of lunar dust in the lunar environment.

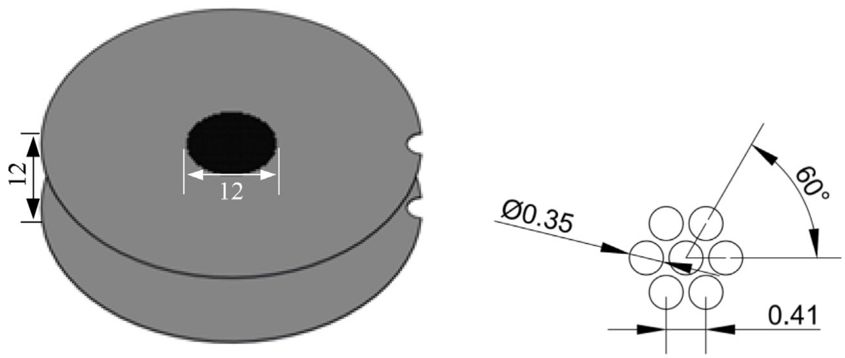

Fig. 3. Structure and geometry of grids. Mesh apertures were only opened in the center area of the grid. The apertures with a size of φ0.35 mm and a separation distance of 0.41 mm are regular triangle arranged.

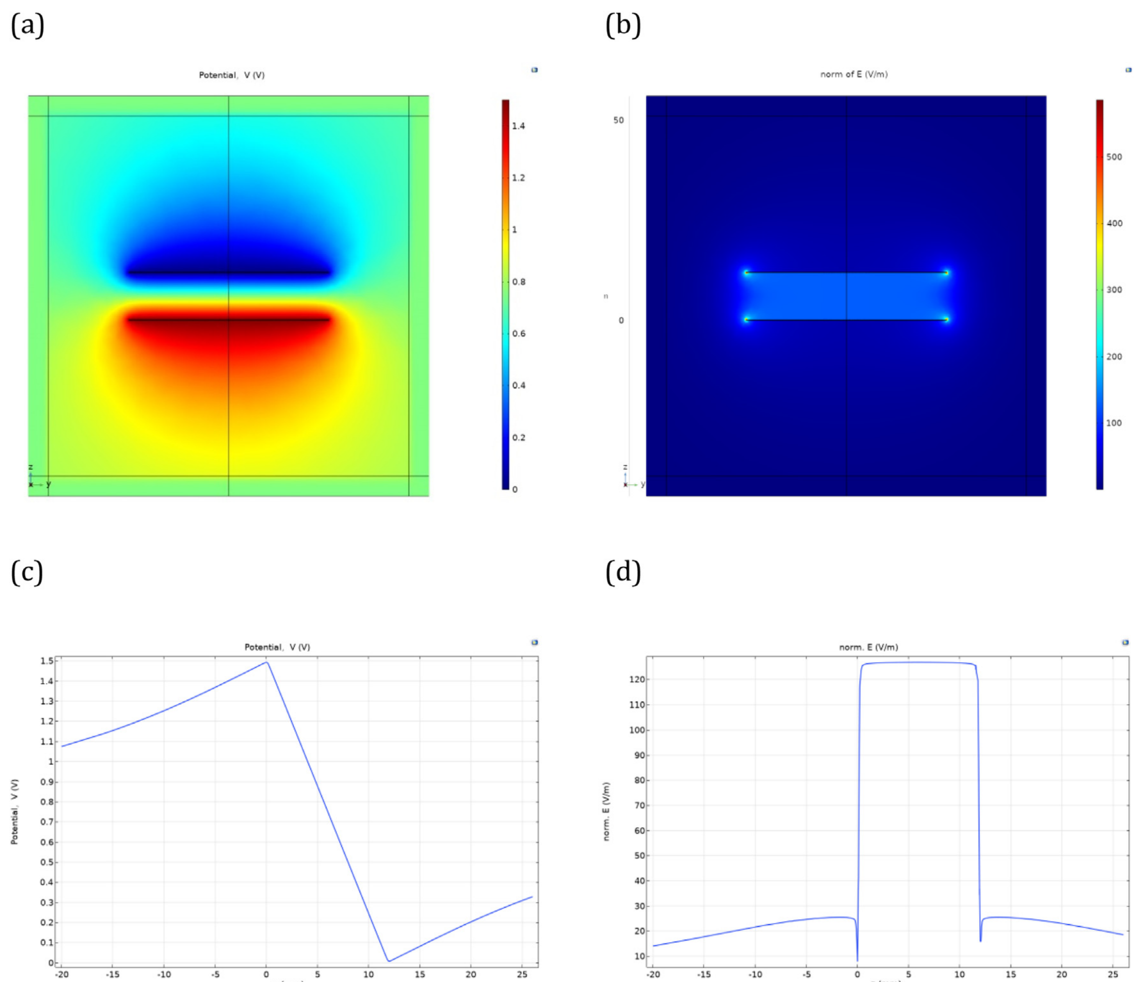

Fig. 4. The simulation results of electric field of the RPA-M. (a) Potential; (b)Electric field intensity; (c)The potential change of center line; (d) The change of electric field intensity of center line. The graphs drown by COMSOL show the information of electric field between two grids. The sweep voltage is set as +1.5 V in this example and the intensity of electric field in the middle is worked out at 127.12 V/m.

SQCM consists of gold electrodes (yellow), quartz crystal (white) and sticky film (green). The sticky film is coated on the sensing surface.

In Chang'E-5 DCLD, SQCM is located 10 mm below the barrier grid, and 10 MHz quartz crystal sensor is used. The sticky film with several microns thick is coated on the quartz crystal sensing surface, and it is made of Apiezon-H vacuum grease, shown in Fig.5. Because of the addition of sticky film and specific measuring object, the sensitivity of SQCM needs to be recalibrated.

3. Methods of detection

Chang'E-5 DCLD consists of two probes with same structure. Each probe has one set of RPA and SQCM. The difference is that there is a certain voltage between the RPA-M grids in the measurement probe, while the RPA-R grids are connected to the Landing Module (LM) structure and it means that they are equipotential. (Shown in Fig. 6)

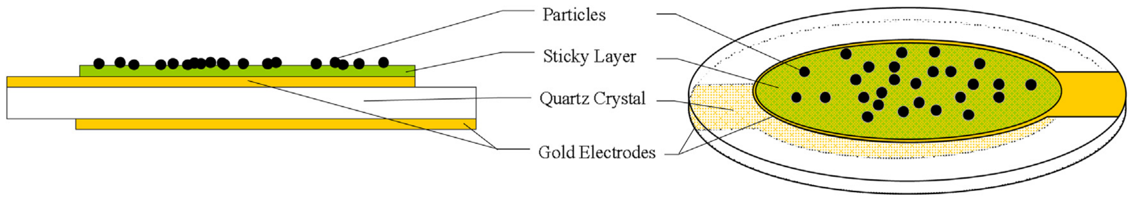

Fig. 5. Schematic diagram of SQCM structure.

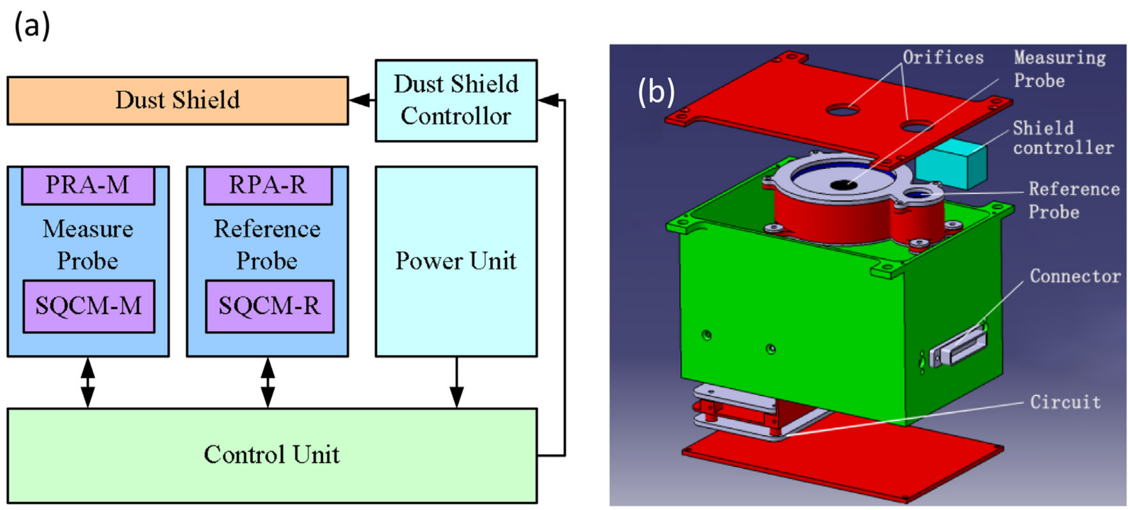

Fig. 6. Main parts of DCLD (a) and the 3D structure (b).

DCLD detector is composed of two probes, dust shield with controller, power and control units. The dust shield could be opened and closed by command, and it could protect the probes from unexpected dust or harsh environments when the detector is not working. The control unit is used to control the probes and collect information.

According to previous theory and observation [29–31], there are large amount of levitated dust over the moon surface. Generally, those dust particles achieve a force balance under the action of electrostatic force and gravitational force, which is like as:

$$QE_m \approx mg_{\rm m} \tag{1}$$

Where, Q is the charge of dust particle, E_m is the electric field of the moon surface, m is mass of dust particle, and $g_{\rm m}$ is gravitational acceleration of moon.

In these mechanical conditions, lunar dust particles move up and down at a certain height on the surface of the moon with electric field variation. We consider that it is possible if a particle above the probe should fall into the opened orifices of the detector. Since both the first grid and the second grid are structurally connected to the lander, the electric field of the lunar surface is shielded. Once a charged particle enters the reference probe, it will only be affected by the gravity, and will pass through the grids of RPA and adhere to the SQCM below. Therefore, the mass of all dust entered to the reference probe will be monitored.

While if a charged dust particle enters the measuring probe, as the $E_{\rm m}$ is shielded, the dust particle will only be acted by the electric field force between grids and the gravity of the moon. The forces upon one dust particle (red one) is shown in Fig. 7.

This picture shows the working principle when a positive sweep voltage applied for RPA-M. Some of dust particles (black dots) positive charged are blocked or pushed out of the measuring probe when the dust cloud falling to the probes.

Supposed the sweep voltage is $U_{\rm i}$, then the electric field intensity $E_{\rm i}$=$U_{\rm i}$/d, where d is the vertical spacing of the grids. If the particles are positively charged, the charge is Q, when the Coulomb force is greater than the gravity; the particles will be suppressed and cannot reach the SQCM surface. For these particles,

$$QE_i \geq {\rm m}g_m \tag{2}$$

It means if a particle with a charge to mass ratio $\frac{Q}{m} \geq \frac{d \cdot g_m}{U_i}$, it cannot be measured by SQCM. The $E_{\rm i}$ in the probe can be changed by adjusting the sweep voltage $U_{\rm i}$, so that we can change the range of charge/mass ratio of suppressed dust. In this situation, the measured results of two SQCMs are not same in a same period of time. The mass difference between SQCM-R and SQCM-M, Δm is considered to be the mass of dust which has a higher charge to mass ratio than $\frac{d \cdot g_m}{U_i}$. As the relation of the charge/mass ratio and sweep voltage of the probe, the trends of the Q/m ratio with $U_{\rm i}$ has been drawn in Fig. 8.

As an example, assuming U_9 and U_{10} are two steps of sweep voltage, the proportion of charged dust which satisfied $\frac{\rm Q}{\rm m} > \frac{d \cdot g_m}{U_9}$ can be calculated by $\frac{\Delta {\rm m}_9}{m_0} \times 100\%$; the proportion of charged dust which satisfied $\frac{d \cdot g_m}{U_{10}} > \frac{Q}{m} > \frac{d \cdot g_m}{U_9}$ can be calculated by $\frac{\Delta {\rm m}_9 - \Delta {\rm m}_{10}}{m_0} \times 100\%$. The procedure of data processing is shown in Fig. 9.

The raw data of the detector is frequency of SQCM. The mass of deposited dust can be calculated from the frequency and the Sauerbrey function. m_0 is the total mass of the dust deposited on the reference probe.

4. Results and discussion

Because it is difficult to simulate the exactly same lunar dust environment on the ground, especially the lunar gravity and the real lunar dust particles, so it is impossible to carry out a complete simulation and verification experiment. However, we can test the sensitivity of SQCM and the blocking effect of RPA grid to show the effectiveness of the design.

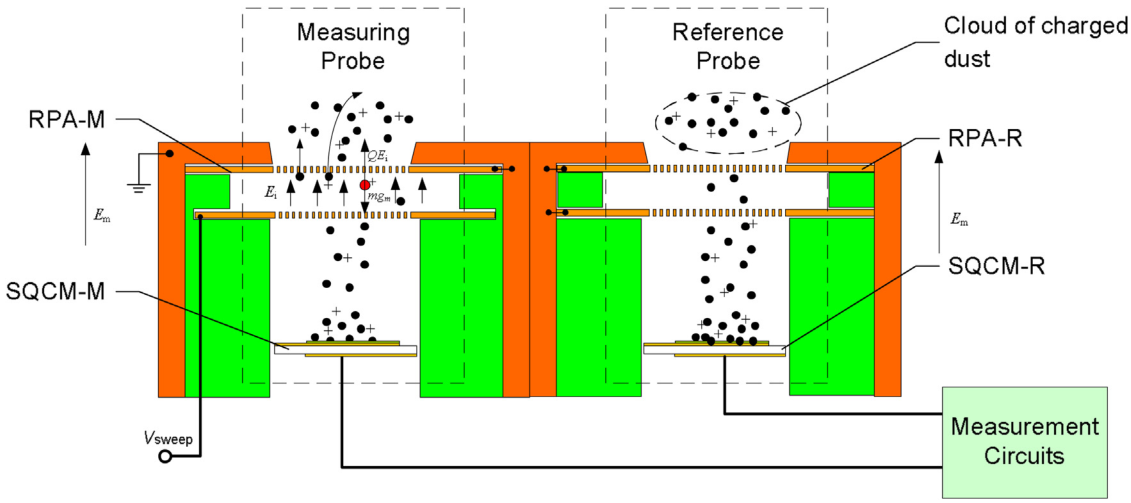

Fig. 7. The measuring principle of DCLD.

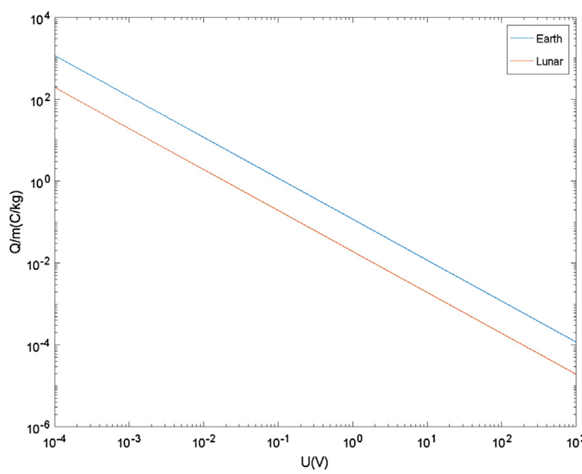

Fig. 8. The range of suppressed dust's Q/m with different voltage of the m-probe. Blue line describes the trend under Earth's gravity and the red line indicates the trend under the moon's gravity.

4.1. Sensitivity of SQCMs

The sensitivity coefficient of a QCM is related to the natural property of crystal when it is used to measure the molecular contamination. But we found that the sensitivity coefficient of quartz crystal coated with sticky film will change. The sensitivity coefficient of 10 MHz uncoated quartz crystal microbalance is 4.42×10^{-9} g/Hz·cm^2, but the addition of sticky film changes the vibration characteristics of crystal and the specific measuring object, solid particles which is very different with the molecules, so it is necessary to be calibrated for the sensitivity coefficient.

In the calibration test, we used the simulated lunar dust particles CLDS-1 for the experiment. CLDS-1 lunar dust simulant was developed by Institute of Geochemistry, Chinese Academy of Sciences. The size distribution and mineral and chemical composition of CLDS-1 particles can be briefly sketched that, $D_{100} \leq 20$ μm, $D_{95} \leq 2.5$ μm, $D_{50} \leq 0.3$ μm, the glasses content 55 % and the main element of chemical composition is close to lunar dust [32].

In addition, we found that the no-load frequency stability and the measuring ability of SQCM have better performance, when SQCM is used in vacuum than that in air. In order to obtain the data more suitable for its working scene, the calibration experiment should be carried out in vacuum.

Through a set of dust strewing machine placed in the vacuum chamber (the working pressure <7×10^{-3}Pa), the dust simulants can be relatively evenly dropped into the DCLD. Four dust collector plates were placed around the probe and reference probe, as shown in Fig.10. Before and after each experiment, a high-precision Electronic Balance (METTLER-TOLEDO XP2U, 0.1 μg) was used to weigh the mass of the collector plates, and then the surface density of dust at four plates were obtained. The mass on the SQCM was calculated by averaging over the deposition mass on the four plates. The reason for this treatment is to minimize the error caused by uneven distributed dust strewing.

On the basis of same procedures, the sticky film must be coated again to make sure a new state of SQCM before each test. After dozens of tests, we obtained a series of data of frequency shift and area density of dust mass. The calibration data and fitting curve of the sensitivity coefficient of the measuring and reference crystal are shown in Fig.11. It can be seen that the SQCM of the measurement and reference probe shows a fairly good linear relationship, although some of data seems a little dispersed that probably caused by kinds of experiment errors. With the help of data analysis tools, we carried on the linear fitting to those data, and then determined the relevant parameters. The sensitivity coefficient of measuring probe is S_M=(8.002 ± 0.510)$\times 10^{-9}$g/Hz·cm^2, and that of reference probe is S_R=(9.137 ± 0.369)$\times 10^{-9}$ g/Hz·cm^2. Through the test, we can also estimate the linear measurement range of the probes conservatively. In general, 30 kHz is considered the maximum linear frequency shift, and 1 Hz is the minimum measurable frequency, so that, the measurable range of QCM-R is about 9.1 ng/cm^2∼0.27 mg/cm^2 and the range of QCM-M is about 8.0 ng/cm^2∼0.24 mg/cm^2.

4.2. Inhibition of charged particles by RPA

The experiment was designed to verify the inhibitory effect of RPA on lunar dust particles.

4.2.1. Acquisition of charged particles

It is a common method to make particles charged by friction with different materials. It is pointed out in reference [33], that the total charge per mass value of JSC-1A under high vacuum (10^{-5} Torr (10^{-3}Pa)) can reach 629 ± 58 nC/g. It was found also in our experiments that, after a same treatment, the dust particles would always have a certain range of charge to mass ratio.

In this experiment, we used CLDS-1 lunar dust simulant also, and the dust should be stored at 130 °C for 3 h before they were put in to the dust strewing equipment. The dust strewing equipment is

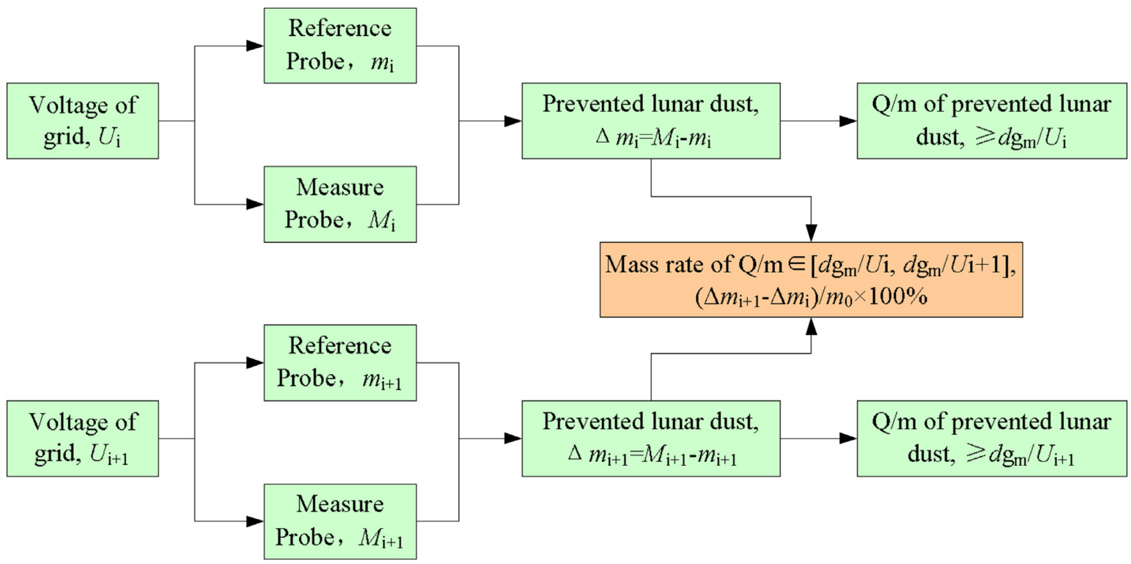

Fig. 9. Flow chart of data processing.

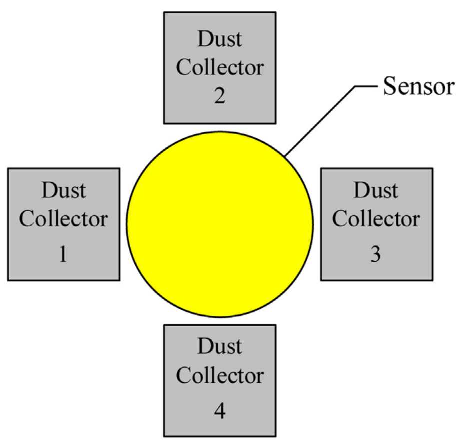

Fig. 10. Sketch of the positions of dust collectors.

mainly made of stainless steel, as shown in Fig. 12. The stainless steel brush and mesh will rub against the dust particles adequately when the stewing device is working. Since the work function of the lunar dust simulant is higher than that of the stainless steel, the particles will be negatively charged after they scattered from the device.

The dust strewing equipment is composed of a rotating motor, a steel brush, and a steel mesh. The lunar dust simulant put into the equipment could be stirred by the brush and strew out through the steel mesh. Lunar dust particles would be charged in this process, and then they fall down and measured by Faraday Cup. All of the process should be finished in vacuum.

In a vacuum chamber (10^{-3}Pa), we use a Faraday Cup, as shown in Fig.12, and a Keithley 6517B Electrometer/High Resistance Meter, of which charge measurements from 10 fC to 2.1 μC, to measure the accumulated charge of lunar dust simulant. The collected mass of dust in Faraday Cup was also weighted by Electronic Balance, and then the Q/m can be calculated. The charge mass ratio of lunar dust simulant was measured for several tests. As shown in Fig.13 below, the average charge mass ratio is about $(6.01 \pm 0.91)\times 10^{-4}$C/kg. The value is very near with the reported value of the reference [33].

Note: We omitted the negative sign when describing the charged quantity of lunar dust simulant particles in the experiment.

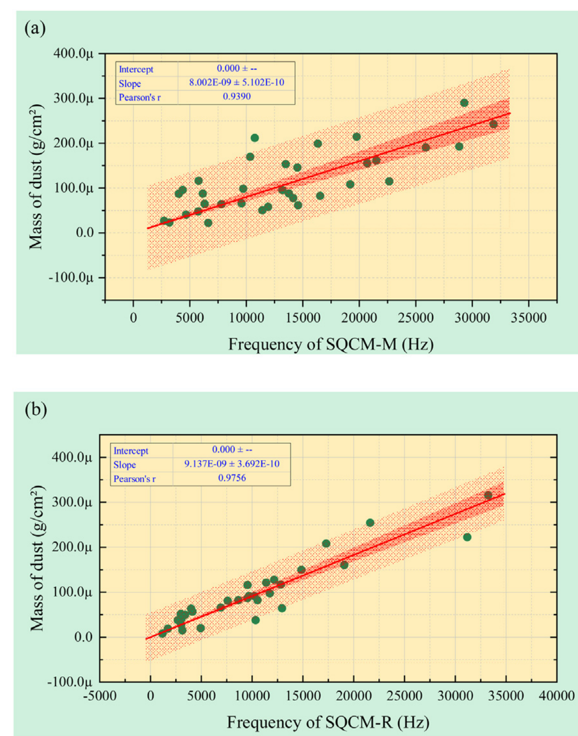

Fig. 11. Sensitivity coefficient data and curve of SQCMs, (a)-Measuring probe; (b)-Reference probe.

4.2.2. Testing and verifying

In order to verify the blocking effect of the grid on the charged dust particles, the particles were charged with the treatment above, and then dropped to DCLD through the dust strewing device in vacuum chamber. The sweep voltage of RPA-M was set different steps from 0 V to -500 V, and the results of SQCM measurement were compared with those without bias voltage.

When the sweep voltage of RPA-M was set at 0 V, it means the measuring probe and the reference probe were exactly the same. We had repeated for many times of this test, and the difference of mass between SQCM-M and SQCM-R are shown in Fig. 14.

It can be seen from Fig. 14 that the mass measured by the measurement and the reference value are almost equal, when the grid

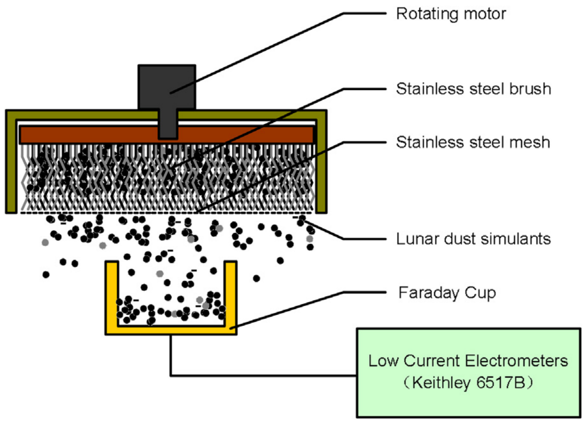

Fig. 12. The dust strewing equipment and Faraday Cup measurement system.

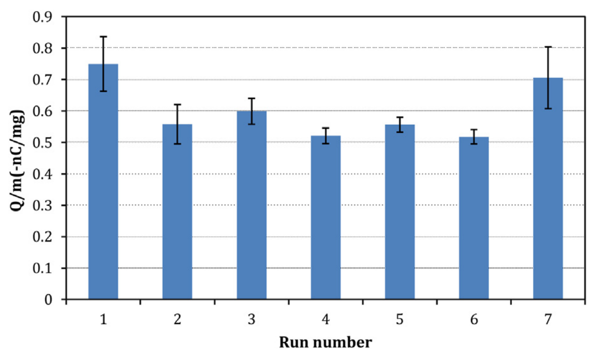

Fig. 13. Measurements of Q/m of tribocharged lunar dust simulant.

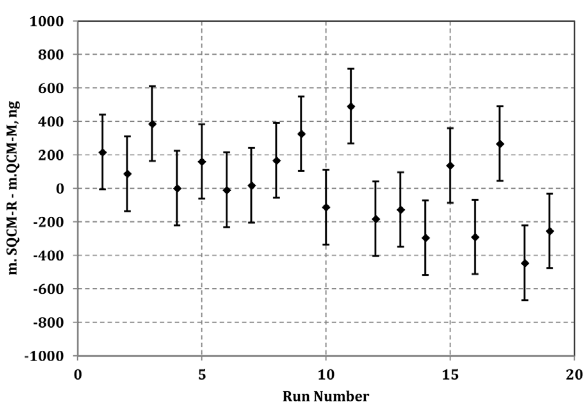

Fig. 14. Difference of measurement mass @sweep voltage = 0 V.

voltage of RPA-M is set to zero. In the ideal case, the SQCM-M value subtract SQCM-R value should be equal to 0. However, due to the non-uniformity of the dust distribution, there is a deviation between them. According to the experimental results, the average value of all tests is 28.3 ng/cm^2, which close to zero, and the standard deviation is 255.7 ng/cm^2.

When we try to change the sweep voltage of RPA-M, with differential step length increasing from 0 V to -500 V, we find the mass measured by SQCM-M became more less than that of SQCM-R. In order to obtain the trend of mass change via sweep voltage, we calculate the relative mass change with the relation below,

$$R_m = \frac{m_{ref} - m_{mea}}{m_{ref}} \times 100\% \tag{3}$$

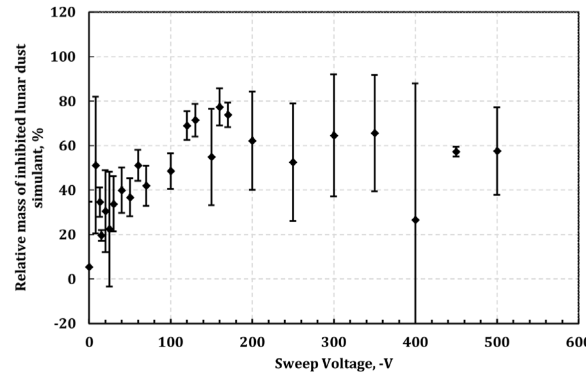

Fig. 15. Relative mass changes with different sweep voltage.

where $R_{\rm m}$ is relative mass change, m_{ref} is mass on reference probe, m_{mea} is mass on measuring probe. The experiment data is shown in Fig. 15

Fig.15 shows the relative mass change between the measured value and the referenced value with increasing of sweep voltage. Compared with the test results with the sweep voltage 0 V (Fig.14), we could find an obvious trend, that is, after the sweep voltage exerted on the measuring probe, the dust mass measured by the measuring probe is significantly reduced compared with the reference probe. Because there are many uncertain factors affecting the measurement, such as the non-uniformity error of dust strewing device, the charge instability error of lunar dust simulants, and the measurement error of SQCM, and the data fluctuate quite greatly. However, through the data, we can still see that with the increase of the sweep voltage in the range of 0 V ~-200 V, the proportion of the suppressed particles increases. According to a rough data analyses, when the voltage scanning from 0 V to -100 V, the proportion of dust suppressed increases rapidly; when the sweeping voltage reaches -200 V, about 50 % of the dust is suppressed, and then the inhibition growth rate become flatter.

The average charge to mass ratio of lunar dust simulants is (6.01 ± 0.91)×10^{-4} C/kg. It means there should be lots of the dust particles are in accord with this value. According to the theory analysis above, the voltage required to suppress most of the lunar dust simulants particles is as follows:

$$U_i \geq \frac{dg_e}{\frac{Q}{m}} = 196V \tag{4}$$

It quite fits the experimental results.

Therefore, it is reasonable for us to consider that the DCLD has the functions to measure the charged characteristics of lunar dust, and obtain a distribution of charge to mass ratio.

4.3. Working at lunar surface

According to the theory of lunar dust charging [34–37], assuming that the dust particles are spheres, the electric charge of lunar dust under vacuum can be estimated by:

$$Q = 4\pi\varepsilon_0 r_d \Phi_d \tag{5}$$

Where Φ_d is the charged potential of isolated particles, r_d is the radius of particles, and if the density of lunar dust is ρ the mass of dust

$$m = \frac{4}{3}\pi r_d^3 \rho \tag{6}$$

Therefore, the charge mass ratio of a single lunar dust is

$$\frac{Q}{m} = \frac{4\pi\varepsilon_0 r_d \Phi_d}{\frac{4}{3}\pi {r_d}^3 \rho} = \frac{3\Phi_d \varepsilon_0}{\rho {r_d}^2} \tag{7}$$

Table 1
Technical specifications of the DCLD.

Parameters	Specifications
Sensitivity of SQCM, g/Hz·cm^2	S_M = (8.002 ± 0.510) × 10^{-9} S_R = (9.137 ± 0.369) × 10^{-9}
Measurement range of SQCM, mg/cm^2	QCM-R: ~0.27 QCM-M: ~0.24
Sweep voltage of RPA-M, V	−500~+500
Working temperature, °C	−20~+50
Size, mm^3	112 × 74 × 69
Weight, kg	≤0.370
Power, W	≤3

Assume ρ = 3000 kg/m^3, ε_0 = 8.85 × 10^{-12}F/m [38], then

$$\frac{Q}{m}\left(C/kg\right) = 8.85 \times 10^{-3} \times \frac{\Phi_d(V)}{{r_d}^2} \tag{8}$$

Therefore, when the surface potential of the moon is constant, the charge mass ratio is proportional to $1/{r_d}^2$.

As a result, when the RPA-M is working, the particles with small particle size are easier to be blocked because of the higher charge mass ratio. Since the acceleration of gravity on the moon is one sixth of that of the earth, the suppression voltage required on the moon to hold back the particles with the same charge mass ratio is 1/6 of that of the earth, as shown in Fig. 9. We have verified the inhibitory effect of RPA-M in the ground test. It is reasonable to consider that the inhibition effect of RPA-M is more obvious on the moon.

There are many errors in analog experiment on the earth, such as the non-uniformity error of dust deposition and the charging instability error of lunar dust simulant, that are difficult to overcome in the laboratory on earth. However, in lunar natural environment, the deposition uniformity and charge stability of lunar dust will be greatly improved. Therefore, the DCLD could performance more stable.

5. Conclusions

In this paper we introduced the main components of DCLD, the measuring principle and the experimental results. We determined the sensitivity of SQCM and verified the blocking effect of RPA grid. To sum up the main characteristic parameters of DCLD, we list them in the following table (See Table 1).

In addition, if only the reference probe be used, it is a mass detector which could measure solid micro particles with a high sensitivity of ng/cm^2. We can get the information of lunar dust deposition mass if it used on the surface of moon. If we combine the measurement probe data, we can obtain the proportion distribution of dust with different charge mass ratio.

Therefore, compared Faraday Cup and ELDA method, we consider that DCLD is a compact device, which can not only measure the accumulated mass of lunar dust in situ, but also measure the charged characteristic of lunar dust in situ.

Using this detector will supplement people's understanding of the characteristics of lunar dust. After some corresponding improvement accomplished, this method could also be applied to the measuring of charged dust on the earth and Mars.

6. Author-statement

I have made substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND I have drafted the work or revised it critically for important intellectual content; AND I have approved the final version to be published; AND I agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

All persons who have made substantial contributions to the work reported in the manuscript, including those who provided editing and writing assistance but who are not authors, are named in the Acknowledgments section of the manuscript and have given their written permission to be named. If the manuscript does not include Acknowledgments, it is because the authors have not received substantial contributions from nonauthors.

Declaration of Competing Interest

The authors report no declarations of interest.

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References

[1] M. Horányi, Charged dust dynamics in the solar system, Annu. Rev. Astron. Astrophys. 34 (1996) 383–418, http://dx.doi.org/10.1146/annurev.astro.34.1.383.
[2] E. Grün, M. Horányi, Z. Sternovsky, The lunar dust environment, Planet. Space Sci. 59 (2011) 1672–1680, http://dx.doi.org/10.1016/j.pss.2011.04.005.
[3] E. Grün, M. Horányi, A new look at Apollo 17 LEAM data: nighttime dust activity in 1976, Planet. Space Sci. 89 (2013) 2–14, http://dx.doi.org/10.1016/j.pss.2013.10.005.
[4] M. Horányi, Z. Sternovsky, M. Lankton, et al., The lunar dust experiment (LDEX) onboard the lunar atmosphere and dust environment explorer (LADEE) mission, Space Sci. Rev. 185 (2014) 93–113, http://dx.doi.org/10.1007/s11214-014-0118-7.
[5] H. Zhang, Y. Wang, L. Chen, H. Zhang, et al., In-situ lunar dust deposition amount induced by lander landing in Chang'E-3 mission, Sci. China Ser. E Technol. Sci. 063 (2020) 520–527, http://dx.doi.org/10.1007/s11431-019-1434-y.
[6] D. Li, Y. Wang, H. Zhang, J. Zhuang, X. Wang, Y. Wang, et al., In situ measurements of lunar dust at the Chang'E-3 landing site in the northern Mare Imbrium, JGR: Planets 124 (2019) 2168–2177, http://dx.doi.org/10.1029/2019JE006054.
[7] D. Li, Y. Wang, H. Zhang, X. Wang, Y. Wang, Z. Sun, et al., *In-situ* investigations of dust above the lunar terminator at the Chang'E-3 landing site in the Mare Imbrium, Geophys. Res. Lett. 47 (2020), http://dx.doi.org/10.1029/2020GL089433, e2020GL089433.
[8] L. Xie, X. Zhang, L. Li, B. Zhou, Y. Zhang, Q. Yan, et al., Lunar dust fountain observed near twilight craters, Geophys. Res. Lett. 47 (2020), http://dx.doi.org/10.1029/2020GL089593, e2020GL089593.
[9] T.J. Stubbs, R.R. Vondrak, W.M. Farrell, A dynamic fountain model for lunar dust, Adv. Space Res. 37 (2006) 59–66, http://dx.doi.org/10.1016/j.asr.2005.04.048.
[10] J. Wang, X. He, Y. Cao, Modeling electrostatic levitation of dust particles on lunar surface, IEEE Trans. Plasma Sci. 36 (2008) 2459–2466, http://dx.doi.org/10.1109/TPS.2008.2003016.
[11] M.K. Mazumder, R. Sharma, A.S. Biris, M.N. Horenstein, S. Trigwell, M.M. Abbas, Electrostatic and Gravitational Transport of Lunar Dust in the Airless Atmosphere of the Moon, IEEE IASAM, 2008, pp. 1–4, http://dx.doi.org/10.1017/S1477200008002661.
[12] X. Wang, M. Horányi, S. Robertson, Dust transport on a surface in plasma, IEEE Trans. Plasma Sci. IEEE Nucl. Plasma Sci. Soc. 39 (2011) 11, http://dx.doi.org/10.1109/TPS.2011.2132147.
[13] A.R. Poppe, M. Piqette, A. Likhanskii, M. Horanyi, The effect of surface topography on the lunar photoelectron sheath and electrostatic dust transport, ICARUS 221 (2012) 135–146, http://dx.doi.org/10.1016/j.icarus.2012.07.018.
[14] S.I. Popel, L.M. Zelenyi, A.P. Golub', A.Y. Dubinskii, Lunar dust and dusty plasmas: recent developments, advances, and unsolved problems, Planet. Space Sci. 156 (2018) 71–84, http://dx.doi.org/10.1016/j.pss.2018.02.010.
[15] I.A. Kuznetsov, A.V. Zakharov, G.G. Dolnikov, et al., Lunar dust: properties and investigation techniques, Sol Syst Res 51 (2017) 611–622, http://dx.doi.org/10.1134/S0038094617070097.
[16] S. Barabash, Y. Futaana, SELMA: a mission to study lunar environment and surface interaction, EGU General Assembly Conference Abstracts (2007) https://impact.colorado.edu/dap/abstracts/stas_barabash.pdf.
[17] A.K. Kamra, Experimental study of the electrification produced by dispersion of dust into the air, J. Appl. Phys. 44 (1973) 125–131, http://dx.doi.org/10.1063/1.1661846.

[18] B. Walch, M. Horányi, Measurement of the charging of individual dust grains in a plasma, Ieee Trans. Plasma Sci. 22 (1994) 97–102, http://dx.doi.org/10.1109/27.279010.
[19] S.S. Kausik, M. Chakraborty, P. Dutta, et al., Study of charge distribution in a dust beam using a Faraday cup, Phys. Lett. A 372 (2008) 860–865, http://dx.doi.org/10.1016/j.physleta.2007.08.047.
[20] Z. Sternovsky, S. Robertson, A. Sickafoose, J. Colwell, M. Horányi, Contact charging of lunar and Martian dust simulants, J. Geophys. Res. 107 (2002) 5105, http://dx.doi.org/10.1029/2002JE001897.
[21] D.S. Schmidt, R.A. Schmidt, J.D. Dent, Electrostatic force on saltating sand, J. Geophys. Res. 103 (1998) 8997–9001, http://dx.doi.org/10.1029/98JD00278.
[22] N.C. Orger, K. Toyoda, H. Masui, M. Cho, Experimental investigation on silica dust lofting due to charging within micro-cavities and surface electric field in the vacuum chamber, Adv. Space Res. 63 (2019) 3270–3288, http://dx.doi.org/10.1016/j.asr.2019.01.045.
[23] N. Duncan, Z. Sternovsky, E. Gruen, et al., The electrostatic lunar dust analyzer (ELDA) for the detection and trajectory measurement of slow-moving dust particles from the lunar surface, Planet. Space Sci. 59 (2011) 1446–1454, http://dx.doi.org/10.1016/j.pss.2011.06.002.
[24] G.A. Landis, P.P. Jenkins, Dust on mars: materials adherence experiment results from mars pathfinder, in: Conference Record of the 26th IEEE Photovoltaic Specialists Conference, Anaheim, CA, USA, 1997, pp. 865–869, http://dx.doi.org/10.1109/PVSC.1997.654224.
[25] E. Palomba, E.L. Colangeli, P. Palumbo, A. Rotundi, et al., Performance of micro-balances for dust flux measurement, Adv. Space Res. 29 (2002) 1155–1158, http://dx.doi.org/10.1016/S0273-1177(02)00131-X.
[26] B. Kirov, K. Georgieva, E. Apostolov, et al., A retarding potential analyzer for rocket experiments, Adv. Space Res. 2 (1982) 89–92, http://dx.doi.org/10.1016/0273-1177(82)90156-9.
[27] F. Dirri, E. Palomba, A. Longobardo, E. Zampetti, et al., A review of quartz crystal microbalances for space applications, Sens. Actuators A Phys. 287 (2019) 48–75, http://dx.doi.org/10.1016/j.sna.2018.12.035.
[28] O.M. Uy, R.P. Cain, B.G. Carkhuff, A.M. Lennon, Sticky quartz crystal microbalance as a particle monitor, Proc. SPIE 3784, Rough Surface Scattering and Contamination, (25 October (1999), http://dx.doi.org/10.1117/12.366690.
[29] D.R. Criswell, Horizon-glow and the motion of lunar dust, in: R.J.L. Grard (Ed.), Photon and Particle Interactions with Surfaces in Space, Volume 37, Astrophysics and Space Science Library, 1973, p. 545, http://dx.doi.org/10.1007/978-94-010-2647-5_36.
[30] J.E. Colwell, S. Batiste, M. Horányi, S. Robertson, Lunar surface: dust dynamics and regolith mechanics, Rev. Geophys. 45 (2007) 1–26, http://dx.doi.org/10.1029/2005RG000184.
[31] J.E. Colwell, S. Robertson, M. Horányi, et al., Lunar dust levitation, J. Aerosp. Eng. 22 (2009) 2–9, http://dx.doi.org/10.1061/(ASCE)0893-1321(2009)22:1(2).
[32] H. Tang, X. Li, S. Zhang, S. Wang, et al., A lunar dust simulant: CLDS-i, Adv. Space Res. 59 (4) (2017) 1156–1160, http://dx.doi.org/10.1016/j.asr.2016.11.023.
[33] N. Afshar-Mohajer, C.-Y. Wu, N. Sorloaica-Hickman, Electrostatic collection of tribocharged lunar dust simulants, Adv. Powder Technol. 25 (2014) 1800–1807, http://dx.doi.org/10.1016/j.apt.2014.07.010.
[34] J. Captain, S. Trigwell, E. Arens, et al., Tribocharging lunar simulant in vacuum for electrostatic beneficiation, AIP Conf. Proc. (2007) 951, http://dx.doi.org/10.1063/1.2437538.
[35] C. Goertz, Dusty plasmas in the solar system, Rev. Geophys. 27 (1989) 271–292, http://dx.doi.org/10.1029/RG027i002p00271.
[36] N. Afshar-Mohajer, B. Damit, C.-Y. Wu, N. Sorloaica-Hickman, Electrostatic particle collection in vacuum, Adv. Space Res. 48 (2011) 933–942, http://dx.doi.org/10.1016/j.asr.2011.04.030.
[37] R.C. Hazelton, E.J. Yadlowsky, Measurement of dust grain charging in a laboratory plasma, IEEE Trans. Plasma Sci. 22 (1994) 91–96, http://dx.doi.org/10.1109/27.279009.
[38] G.H. Heiken, D.T. Vaniman, B.M. French, Lunar Sourcebook: A User's Guide to the Moon, Cambridge University Press, 1991.

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